POWDER-RDZ: Prototyping a Radio Dynamic Zone using the POWDER platform

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***Abstract*—Radio Dynamic Zones (RDZs) are being explored by the research community as an approach to safely test and evaluate spectrum sharing mechanisms and technologies. There is general consensus in the research community regarding the conceptual architecture of an RDZ. In this paper, we present our work on the POWDER-RDZ, a prototype RDZ developed and built on the POWDER platform. We present a practical RDZ architecture and explore a number of end-to-end use-cases. We present the design and implementation of OPENZMS, our prototype RDZ Zone Management System, and evaluate it in the POWDER platform.**

***Index Terms*—Radio Dynamic Zone, Zone Management System, Spectrum Sharing**

I. INTRODUCTION

Interest in wireless applications continues to grow unabated, and with it continued demand for spectrum. Spectrum is, however, a finite resource and it is widely accepted that *spectrum sharing* will be the only viable approach to address this supply-demand mismatch [1]. Spectrum sharing is not a panacea, however, and incumbent spectrum users are rightly deeply concerned about the possible impact of spectrum sharing approaches on their respective wireless applications.

A concept being pursued by the research community to explore, and hopefully allay, these concerns is a *Radio Dynamic Zone (RDZ)*. In essence, an RDZ is a “spatial volume” at a particular geographic location where wireless experimentation, and spectrum sharing approaches in particular, can be performed in a controlled way and specifically in such a manner that the potential impact on incumbent spectrum users can be reasoned about and monitored so as to understand and reduce the associated impact and risk. RDZs will be equipped with the necessary tools, mechanisms, equipment and processes to realize such safe exploration.

By necessity the realization of an RDZ is quite complex, involving regulatory and technical challenges, as well as buy-in from incumbents and other stakeholders. The research community is actively investigating these challenges, examining solutions and exploring spectrum sharing use-cases that might be enabled by RDZs [2]–[8]. There is general consensus in the research community regarding the conceptual architecture of an RDZ [9]. In this paper, we present our work on the POWDER-RDZ, a prototype RDZ developed and built on the POWDER platform [10]. We make the following contributions:

A practical end-to-end RDZ architecture: Our first contribution is to flesh out the conceptual RDZ architecture into a concrete RDZ design and architecture capable of supporting and experimenting with end-to-end RDZ workflows. A *Zone Management System (ZMS)* (called a Zone Management Engine in [9]) is at the center of an RDZ. We formalize the other key role players in an RDZ, i.e., *Spectrum Providers*, *Spectrum Monitors* and *Spectrum Consumers*, and develop a *Zone Abstraction Layer (ZeAL)* to enable these role players to interact with the ZMS via well-defined interfaces.

End-to-end RDZ use cases: We explore the generality of our RDZ architecture by considering the end-to-end workflows associated with a number of different RDZ use-cases. First, we consider using the ZMS to provide general spectrum awareness and spectrum management in an RDZ: i.e., monitoring incumbent spectrum use and making spectrum allocation/use decisions for experimental transmission systems to ensure safe operation in the RDZ. Second, we examine explicit spectrum sharing in the RDZ with an incumbent mobile wireless provider: e.g., a provider who might temporarily, and for short time-scales, grant use of a part of its spectrum to the RDZ. Finally, we consider spectrum sharing between a sensitive spectrum user: e.g., a weather radar system, or a radio telescope installation used in astronomy exploration.

Prototype RDZ implementation and evaluation: Our main contribution is the prototype realization of the POWDER-RDZ architecture and its evaluation in the POWDER platform. Specifically, we implemented OPENZMS, the POWDER-RDZ ZMS, and used the capabilities of the POWDER platform to facilitate examples of the RDZ role players (spectrum provider, monitor and consumer). OPENZMS is built with a containerized, cloud native approach, where ZMS core functions are realized as loosely-coupled services with well-defined APIs. This design enables a broad range of deployment options, and, critically, enables flexibility in core function implementation. For example, spectrum intelligence and decision making in OPENZMS is realized as a digital spectrum twin

This work was supported by the NSF through the following grants: #1827940, #2232463, #2232464 and #2232465.

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(DST) [5], [6]. We use two RF propagation analysis tools in OpenZMS: an open source version which builds on the TIREM RF propagation model [7], as well as a commercial RF propagation engine which implements several RF propagation models. OpenZMS is a standalone software system that can be deployed to manage any RDZ; Powder integrates with OpenZMS over the ZeAL interface to form Powder-RDZ.

Open source RDZ and end-to-end artifacts: To the best of our knowledge, Powder-RDZ is the first practical end-to-end realization of an RDZ. Our overall objective is for this work to inform and be used by the community to explore RDZ concepts and experiment with spectrum sharing methodologies. To that end, OpenZMS will be released as open source to the community. We will release our Powder-RDZ end-to-end use cases as ready-to-run profiles on the Powder platform to enable others to replicate and build on our work.

II. POWDER-RDZ ARCHITECTURE

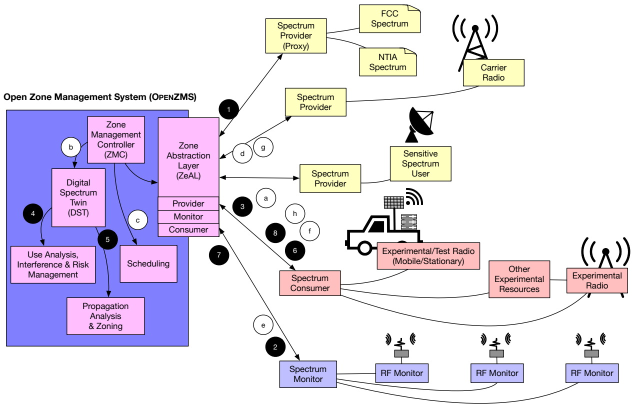

Fig. 1: Powder-RDZ Architecture

The Powder-RDZ architecture is depicted in Figure 1.

The most critical aspect for an RDZ is to have *access to spectrum* that can be used for testing and/or spectrum sharing. The various ways spectrum access might be realized is captured by the *Spectrum Provider* role in Powder-RDZ. As shown at the top of Figure 1, the most basic way an RDZ might obtain access to spectrum is through a licensing process via regulatory agencies, e.g., the FCC and/or NTIA. This might, for example, take the form of special temporary authority (STA), a program experimental license (PEL), or an innovation zone (IZ) designation. Another type of Spectrum Provider involves an incumbent spectrum "owner" (or lessee) who collaborates with the RDZ to enable use/sharing with *their* spectrum. (Note that in these cases there is active spectrum sharing between the Spectrum Provider and the RDZ which is managed/controlled by the RDZ's Zone Management System.) Figure 1 shows two examples of this type of Spectrum Provider. First, a mobile carrier, who, for example during periods of low demand, might temporarily allow use of specific spectrum bands in the RDZ, while retaining the right to dynamically revoke such permission whenever their demand increases. Second, a sensitive spectrum user, such as a radio telescope array, coordinates its spectrum use schedule with the RDZ, thus enabling spectrum sharing in its allocated band; but retaining the right to revoke that permission if an astronomy event changes its planned operation.

Of course, the reason to have an RDZ is to enable testing of radio transmission systems and/or spectrum sharing approaches. As shown in Figure 1, this is captured by the *Spectrum Consumer* role in Powder-RDZ. We anticipate many realizations of this role. For example, a standalone experimental/test radio system might be temporarily brought into an RDZ and the capabilities of its radio transmission system would be (manually) shared with the zone operator to determine a space/volume in which it might safely operate. At the other extreme, the RDZ might have other experimental resources, e.g., other radio systems and antennas, compute and networking capabilities, power and mount points, which could be combined with experimental/test systems.

For general spectrum awareness, and to ensure "safe" operation of the RDZ, a robust *Spectrum Monitoring* capability is needed [3]. We again anticipate a variety of Spectrum Monitor realizations in a practical RDZ. Examples include sensors distributed in and around the RDZ that implement location tracking of test radios [2], inline radio monitoring capabilities that are deployed with radio test equipment [11], aerial spectrum sensors for 3-D spectrum awareness [12], or low-cost, ubiquitous RFID tags for spatially-dense sensing [13].

As shown in Figure 1, the final role in the Powder-RDZ is that of the Zone Management System (or, more specifically in our realization the OpenZMS). The ZMS orchestrates and controls the other role players to realize the RDZ. The role of the ZMS is explored in more detail below by considering a number of example end-to-end use-cases.

A. End-to-end Use-cases

Program experimental license (PEL): Perhaps the most basic RDZ use-case involves the use of spectrum associated with a program experimental license or innovation zone designation. I.e., the RDZ is allowed to use the spectrum range for testing, but should take steps to ensure it is not interfering with incumbent spectrum users and doesn't cause interference outside the zone. With reference to Figure 1 (steps #1-8): (1) At startup the ZMS is initialized with information about the RDZ, and specifically with any information about PEL spectrum ranges the RDZ might operate in. (2) The ZMS requests Spectrum Monitor(s) to perform monitoring of the associated spectrum ranges to provide spectrum intelligence for subsequent RDZ operations. (3) Assume that an experimental 5G system in the RDZ requests spectrum to perform a test. The request might take the form of *XX MHz in the range YY-ZZ MHz*, i.e., to match the capabilities of the 5G system. (4) Using the information provided in the Spectrum Consumer request, the ZMS consults with the DST to determine if the request can be satisfied. In our example the outcome of that query, using data provided by the monitoring system, will be that the request can be satisfied in a specific sub-range of the PEL spectrum. (5) The ZMS will also use the DST to ensure that the 5G system, operating at the power levels indicated in the request, will not cause interference outside of the RDZ.

(6) The ZMS then informs the Spectrum Consumer to proceed with testing of the experimental 5G system. (7) Should the Spectrum Monitor report a violation by the 5G system (e.g., transmitting outside the allocated range, or transmitting at a power level that would cause interference outside the RDZ), (8) the ZMS will instruct the Spectrum Consumer to take measures to immediately cease 5G test transmissions.

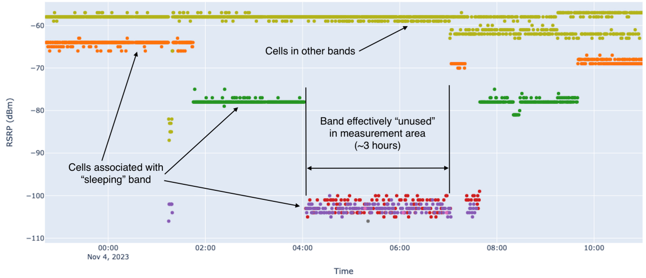

Fig. 2: Example of cells being “idled” resulting in the band in question effectively being unused at the measurement location

Cooperating mobile carrier: The second use-case depicted in Figure 1 involves spectrum provided by a cooperating mobile carrier. We assume that this spectrum is not a long term sub-lease, but a band that can only be used by the RDZ when not in use by the carrier (i.e., when the carrier explicitly informs the RDZ that the spectrum is not in use). As suggested earlier, this might occur when a provider temporarily idles base stations during periods of low demand to reduce energy usage. Figure 2 shows an example of this behavior in the POWDER area. The figure shows RSRP values reported by a COTS UE in POWDER that are associated with different cells reachable by the UE. The data points at the top are associated with cells operating in bands that are not subject to idling (cells in other bands), while the other data points are all associated with different cells in the band that are subject to being idled (cells associated with “sleeping” band). The effect of this behavior is that there is a period of approximately three hours where the “sleeping band” will *effectively be unused* in the area.[1] For our use-case we assume that the cooperating provider will inform the RDZ when this happens, thus allowing the RDZ to make use of the unused spectrum.[2]

The end-to-end flow associated with this use is depicted in Figure 1 (steps #a-h) and proceeds in a similar manner as the PEL use-case: (a) An experimental 5G system in the RDZ requests spectrum to perform a test, and communicate its requirements to the ZMS. (b) As before, the ZMS consults with the DST to determine if the request can be satisfied. In our example the outcome of that query will be that the request can be satisfied, *but only* when the spectrum is not in use by the carrier. Assume that at the time the ZMS receives this Spectrum Consumer request, the carrier is still using its spectrum. (c) The ZMS notes the outcome of this decision and schedules the Spectrum Consumer request to be satisfied once the spectrum becomes available. (d) At some later time the carrier informs the ZMS that the spectrum range is not in use. The ZMS realizes that the Spectrum Consumer request can be satisfied and, as before, (e) makes a request to perform monitoring to detect violations, (f) and informs the Spectrum Consumer to proceed with testing of the experimental 5G system. (g) We assume that the carrier anticipates starting to operate in the band again and communicates that to the ZMS. (h) At this point the ZMS system informs the Spectrum Consumer to cease use of the carrier’s spectrum band.

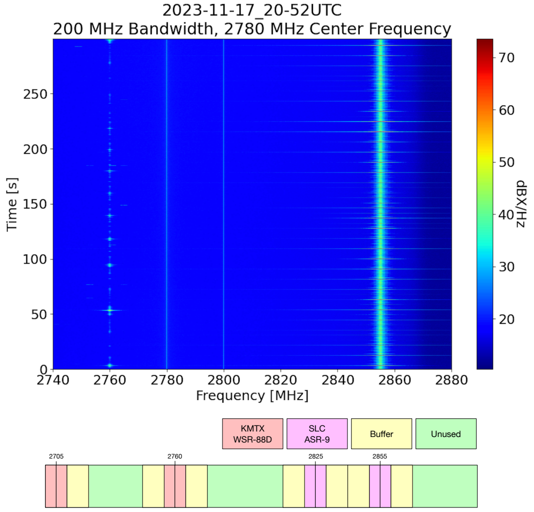

Fig. 3: Radar occupancy in POWDER area (2.74-2.88 GHz)

Cooperating weather radar system: Sharing with weather radar systems presents a use-case that is conceptually similar to the carrier sharing use-case, but from technical, safety and regulatory perspectives provides unique challenges. For example, consider sharing with weather radar systems using the 2.7-2.9 GHz range. This band is used by NOAA’s Next Generation Weather Radar (NEXRAD) systems, as well as airport surveillance radar systems (ASR-9), which is used by the FAA to monitor civilian and commercial air traffic [14]. These are safety-of-life systems that are always operational [14], and indeed have been subject to interference from licensed radio communications systems operating *above* the radar band [15]. Nonetheless, assuming safe sharing mechanisms can be realized, this does present a spectrum sharing opportunity. For example, Figure 3 shows a spectrogram of the 2.74-2.88 GHz range in the vicinity of the POWDER platform, as well as the primary/secondary operating frequencies associated with the two radar systems operating in our area. The spectrogram shows the NEXRAD system operating at 2.76GHz and the ASR-9 at 2.855GHz.[3] As suggested by the occupancy representation at the bottom of the figure, and assuming a 10MHz buffer area around the radar operating ranges, a significant portion of the band (*in this case*) is effectively unused. (This

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[1] I.e., at these low RSRP values (e.g., less than -100 dBm in our example), UEs will switch to using cells with better RSRP values associated with the other bands.

[2] As can be expected and confirmed by our example measurements in Figure 2, these sleeping periods would typically happen during off-peak hours. (In Figure 2 from 4am to 7am local time.) Note that, while likely not generally useful, for an RDZ, access to spectrum for testing will be highly useful even when such access occurs during the night.

[3] The wider signals associated with the ASR-9 system is the result of clipping in our collection system.

may not be true in other geographic areas with additional operational radar systems.) Further, a notification system, interacting with the ZMS, where the secondary operating range of the radar system is shared when the primary is in use (and vice versa), will offer additional sharing opportunities.[4]

Cooperating radio telescope: Our final example use-case involves a cooperating sensitive passive spectrum user such as a radio telescope array. In this case, the radio telescope would provide the ZMS the location of antennas, the spectrum it uses, sensitivity levels, and more. Further, the radio telescope would communicate its anticipated spectrum use (receive) schedule, and the RDZ would be allowed to schedule use of that spectrum in the resulting time-and-frequency gaps. The radio telescope might, however, dynamically preempt use of its spectrum to explore an emerging astronomical event. This use case maps to a similar set of flows between RDZ components as described above. However, because of the sensitivity of the instrument, both the analysis being performed by the ZMS (and its DST), and the sensitivity of monitors deployed to detect violations may differ.

III. OpenZMS

To manage POWDER-RDZ, we are building OpenZMS, an open-source, end-to-end zone management system. In this section, we describe the design and implementation of the services, interfaces, and data models that comprise OpenZMS. OpenZMS employs a centralized spectrum management approach, where spectrum consumers operate under explicit, dynamic delegations of authority from OpenZMS services. This design ensures that OpenZMS can remain in control of an RDZ: it can implement flexible policy-based sharing while still providing protections from harmful interference. OpenZMS is designed and anticipated to manage municipal to regional-scale deployments, with anticipated extensions supporting hierarchical deployments that provide chains of spectrum authority, delegation, and observability.

A. Zone Abstraction Layer (ZeAL)

The Zone Abstraction Layer (ZeAL) realizes the APIs that implement the "logical" *Provider*, *Consumer*, and *Monitor* interfaces presented in Section II. At a more granular level, the ZeAL APIs provide the external, publicly-available, "northbound" interface through which organizations and their members participate in spectrum sharing activities within an RDZ. We refer to a participating organization as an *Element*; Elements are the unit of teaming and collaboration within an organization. Elements provide and update OpenZMS with the configuration of resources that they use within the RDZ (e.g., radio transmitters and receivers), and resources that they offer to the RDZ (e.g., spectrum, radio monitors, infrastructure)—either through an automated Element-side service, or via manual ZeAL API invocations when necessary. *Users* are members of one or more Elements, and may be granted one or more *Roles* in a number of Elements to use spectrum or observe its use; or to perform administrative and operational activities within an Element, such as changing an antenna associated with a radio. We expect that many users of RDZ spectrum will *not* themselves be OpenZMS Users: instead, these Element members may access RDZ resources through user accounts within their organization (Element), and the Element will offer RDZ resources to its own users, via its own abstractions, by consuming the the ZeAL APIs.

To effectively manage an RDZ, OpenZMS defines a data model intended to capture operating characteristics of RDZ radios that consume spectrum. OpenZMS models *Radios* as devices with one or more *RadioPorts*, each of which is connected to an *Antenna*. Radios model the higher-level, generic properties of a device, such as FCC identifier, model, and more. RadioPorts define additional details of operation, such as operating bands, tx/rx modes, maximum power level, and attached antenna azimuth, elevation angle, and location. Antennas define the properties of a specific model of antenna, and can be described via simple properties like gain and beam width; or by detailed radiation patterns (e.g., the widely-used MSI format). OpenZMS does not *operate* these Radios; this information is necessary to enable effective prediction (e.g., propagation simulation) and analysis of measurements (e.g., interference, model accuracy, and more).

OpenZMS's monitoring abstractions build upon these base abstractions. Elements define *Monitors*, associated with particular RadioPorts, which provides detailed reception characteristics to OpenZMS analysis services. Monitors report *Observations*, which contain radio measurement data. The OpenZMS design does not dictate specific measurement and data formats, and accepts processed, indexed, and analyzed information (e.g., occupancy data, power-spectral density), or raw sample data (e.g., SigMF). Our goal is to enable many kinds of services within OpenZMS via horizontally-scalable Observation analysis pipelines. Analysis services may attach additional processed or learned information to Observations as *Annotations* (e.g., an interference and risk analysis).

To delegate spectrum to OpenZMS to manage, Elements create *Spectrum* objects. Each Spectrum object consists of start and end constraints, radio constraints (band, power, area of operation, maximum leakage allowed outside areas of operation, etc), and usage policy (restrictions on particular Elements, priority, required approvals, use models such as when-unoccupied). Elements may revoke Spectrum delegations at any time, which will result in revocation of current and future grants allocated within the revoked Spectrum object. To obtain spectrum from OpenZMS, Elements create *Grant* objects, which consist of the same kinds of start, duration, and radio constraints, and may be associated with one or more RadioPorts. Grant requests may be under-specified across these constraints, allowing OpenZMS to determine a "best fit" allocation of spectrum to the Grant.

B. OpenZMS *components/services*

The OpenZMS ZeAL API is implemented by several services, shown in Figure 4, that provide secure, REST-

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[4] More invasive in-band sharing with radar systems has been proposed [16], but it is unclear whether that could be done in practice.

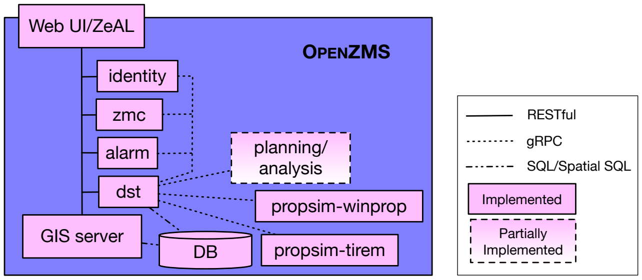

Fig. 4: OPENZMS Implementation

ful endpoints. All services communicate internally over a trusted, RPC-based messaging layer, designed to facilitate high-throughput, low-latency messaging and reactive, event-based analysis pipelines.

1) Core services: The *identity* service provides the Element, User, Role, and Token abstractions and operations. Users can scope Tokens with subsets of their Roles to restrict the set of authorized operations. All OPENZMS services register with the identity service, which maintains a directory to support service-to-service communication.

The *zmc* (zone management controller) service provides the Radio, Monitor, Spectrum, Grant, and related abstractions—it is the primary API endpoint for Elements to populate OPENZMS with radio device information; to provide spectrum for OPENZMS to manage; and for Elements to reserve spectrum via the Grant abstraction. The zmc service currently hosts the spectrum scheduler, which allocates Spectrum to Grants, querying other services as required by policy (e.g. the *dst* service's occupancy data and propagation simulation maps). The zmc service revokes Grants when notified by the *alarm* service that they are in violation of operating constraints.

The *dst* (digital spectrum twin) service provides the Observation, Collection, Annotation, and Propsim (propagation simulation) abstractions. Conceptually, it operates as a dual-purpose system, functioning both as a predictive engine and a data analytics hub. This service indexes records of RF measurements, spectrum usage, and radio device data, and provides a predictive query interface. These queries serve two purposes: 1) determining occupancy, such as verifying the availability of X MHz of spectrum for radio Y at power level Z, at a specific time T, and for a duration D; and 2) estimating a transmission power range for radio Y at time T, ensuring emissions remain below power P outside the RDZ. The *dst*'s analysis capabilities empower it to extrapolate intelligence from short-term observations to identify and understand long-term, spatial spectrum usage trends as exemplified by Figure 5. The dst service stores Observation data in persistent file storage and indexes within appropriate databases (e.g., geospatial, relational, time-series) to support fast queries. It can invoke propagation simulation services on-demand, but can also simulate in expectation of future usage as new Radio and Spectrum objects are created and updated by Elements.

The dst service acts as a client to *propsim* (propagation simulation) services, which generate expected received signal strength maps and other geospatial features for one or more transmitters operating in a given band and power level. These predictions are the basis to facilitate simultaneous, deconflicted shared spectrum use. OPENZMS defines an extensible RPC-based *propsim* job service, and through this interface, the dst service can run parameterized propagation simulations to obtain maps with received signal strength data. The dst service caches and indexes these maps in its PostGIS database to facilitate geographic sharing under a variety of constraints.

2) Analysis services: The *alarm* service analyzes and responds to unexpected interference reports that can occur due to spatial and temporal changes not captured even with sophisticated planning and a multi-dimensional DST. OpenZMS uses monitor observations, along with historical data from the DST, to manage spectrum access for consumers, revoking access from probable interferers. Credible reports from interference events and monitoring data will be used to update the DST for future risk assessments. The primary concern for incumbents is minimizing interference events. This is especially critical for sensitive applications like radio astronomy that have a very small window of acceptable interference [17]. OpenZMS provides a real-time response to unexpected interference reports caused by other RDZ consumers.

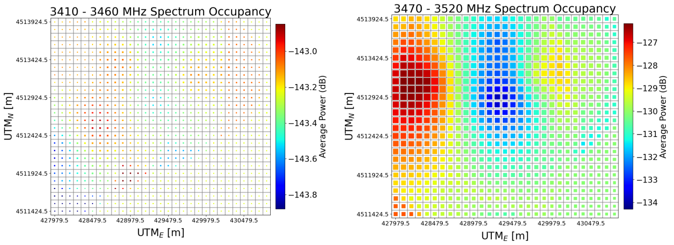

Fig. 5: Spatial spectrum occupancy: 3.41-3.46, 3.47-3.52 GHz

The DST also provides *spectrum planning* services by analyzing long term spectrum monitoring data to provide spatial spectrum occupancy maps. These maps reveal historical usage patterns and availability of specific frequency bands at targeted locations. To illustrate this functionality, we have analyzed spectrum monitoring data from seven different monitors in the RDZ, spanning from June 2022 to November 2023. Our analysis involved identifying a power threshold that distinguishes noise from spectrum usage. We then calculated two key metrics for spectrum occupancy at all monitored sites: the duty cycle and the average occupancy power. After calculating these metrics, we employed spatial interpolation techniques to estimate values for each *proxel*—or propagation picture element—within the RDZ. Specifically, we used a radial basis function interpolation for duty cycle estimations and a Kriging interpolation for average occupancy power. We then synthesized these spatial estimates, correlating the ratio of the area of a square within each proxel to the proxel's total area with its duty cycle. Additionally, the color of these squares visually represents the average occupancy power, with a corresponding colorbar indicating power levels. The result is depicted in Figure 5. Notably, our observations reveal a significantly lower duty cycle and average occupancy power in the 3410-3460 MHz band compared to the 3470-3520 MHz band in the Powder deployment area, aligning with insights from instantaneous monitoring data and reinforcing the data's utility in strategic decision-making processes.

C. OpenZMS Implementation

OpenZMS is built as a set of containerized, cloud-native services to support horizontal scalability for large analysis and prediction workloads, and to facilitate extensibility via third-party services. Each service that provides parts of the ZeAL API does so over a RESTful JSON "northbound" interface. Users authenticate via API tokens and are authorized via role-based access control (RBAC) Internally, services communicate over trusted gRPC service APIs and event streams.

The core identity, zmc, dst, and alarm services are implemented in Golang; the propsim-tirem and propsim-winprop propagation simulation services are implemented in Python. The core services each store data in a relational Postgres database, and the dst further uses the PostGIS extensions to support raster storage of propagation simulation maps and geospatial indexes and queries. We built a web UI that exposes OpenZMS's core abstractions, using the `Vue.js` and `Nuxt.js` frameworks. The UI displays zone status, live measurement graphs, and propagation simulation maps as web map tiles generated and cached by a Geoserver instance, attached to the dst services's PostGIS database.

OpenZMS's *propsim-tirem* service wraps the Terrain Integrated Rough Earth Model (TIREM) [18]. TIREM is a tried-and-true theoretical propagation model that considers physical phenomena such as free space path loss, ground reflection, and diffraction. It has also been shown that TIREM's predictions can be enhanced with measurements collected in the RDZ [7]. OpenZMS's propsim-tirem service exposes a variety of TIREM parameters to control the simulation; parallelizes its execution; and outputs maps as GeoTIFF images that are added to the dst service's database for use in geospatial queries. By default TIREM operates under the assumption of isotropic antenna radiation, an approximation that often diverges from real-world conditions. In contrast, the dst service takes into account the specific radiation pattern of the antenna at the terminal. This approach more accurately represents the antenna's gain distribution across different regions, thereby minimizing the discrepancies caused by relying on the generalized assumption of isotropic radiation.

To illustrate OpenZMS's modularity, and to benefit from other RF analysis tools, we have also implemented the *propsim-winprop* service, based on Feko Winprop, a commercial product from Altair. Winprop provides a range of wireless planning and analysis tools, including RF signal propagation analysis in varied environments. Figure 6 shows a sample RF propagation map produced by this service.

IV. POWDER-RDZ IMPLEMENTATION

While we are realizing Powder-RDZ on the Powder platform, our goal with its design, and specifically the design of OpenZMS, is to produce a generic RDZ architecture and a reference ZMS implementation that will be applicable to a broad range of use cases and RDZ deployments. We used and enhanced the Powder platform to achieve this goal. Specifically, we implemented the OpenZMS *ZeAL interfaces* as a thin abstraction layer that maps to existing Powder functions, and used and enhanced other platform features to provide or emulate Spectrum Provider, Spectrum Consumer and Spectrum Monitor capabilities and to execute variations of the use-cases described in Section II. Figure 7 depicts this implementation and the setup we used for evaluation.

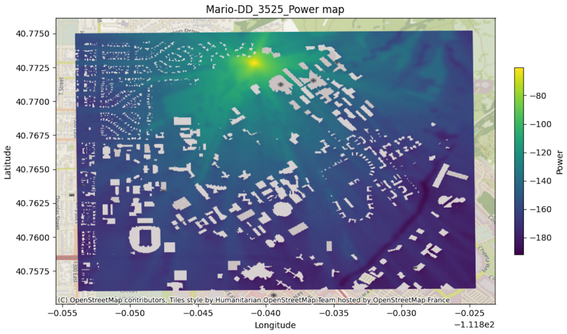

Fig. 6: Example propsim-winprop RF propagation map

ZeAL Spectrum Consumer: Spectrum use in the Powder platform is based on requests associated with our FCC PEL and our FCC IZ designation. The platform also treats spectrum as any other platform resource that can be reserved, allocated, and used by experimenters. For our Powder-RDZ exploration we modified Powder to *cede spectrum control* for a configured spectrum range to the OpenZMS. Specifically, when instantiating an RDZ-related test/experiment in the platform, the normal Powder workflow pauses to request a spectrum grant from the OpenZMS via the ZeAL Spectrum Consumer interface, and resumes once it receives the approved grant from the OpenZMS. Requests from the OpenZMS to stop using spectrum previously granted maps to existing Powder mechanisms to terminate a test/experiment.

The Powder platform is a highly flexible mobile and wireless testbed, and is therefore a good realization of other Spectrum Consumer functions. The platform has the necessary mechanisms to reserve and allocate a variety of wireless equipment (e.g., software-defined-radios (SDRs), commercial-off-the-shelf (COTS) user equipment (UEs) and radio units (RUs)), and to combine that with other platform components (compute nodes, network switches, software stacks) to realize a broad range of functions useful for RDZ testing. For instance, we use the platform's 5G capabilities as our canonical RDZ testing system as described in Sections II and V.

ZeAL Spectrum Monitor: As shown in Figure 7 (light purple elements), we have realized three example implementations of the ZeAL Spectrum Monitor. First, the Powder platform uses *inline spectrum monitoring*, using an RF coupler and specialized software on a dedicated monitoring SDR, to detect any RF transmission violations by experimenters [11]. We implemented the ZeAL Spectrum Monitor interface on this

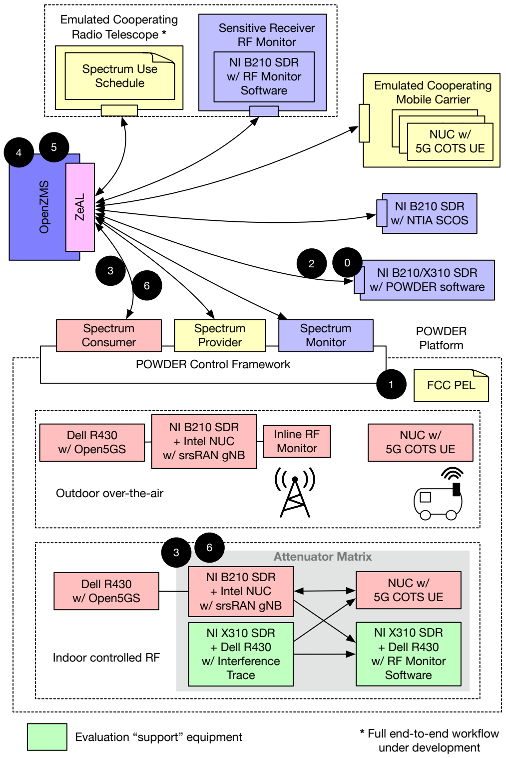

Fig. 7: Implementation and evaluation setup

existing monitoring system to report spectrum violations to the OpenZMS. Second, Powder performs regular (a number of times per day) over-the-air monitoring using all available SDRs in the platform. We added the ZeAL Spectrum Monitor interface to this spectrum monitoring system to report spectrum observations to the ZMS. Third, we used the NTIA/ITS spectrum characterization and occupancy sensing (SCOS) [19] open source software, combined with Powder SDRs, to realize an IEEE 802.15.22.3-compliant OpenZMS monitor.

ZeAL Spectrum Provider: We have also implemented three Spectrum Provider examples (yellow elements in figure 7). First, as noted above, spectrum use in Powder is coupled with our FCC PEL/IZ requests. The platform reports these, or at least the subset associated with RDZ testing, to the OpenZMS via the ZeAL Spectrum Provider interface.

Second, we have developed a *carrier sleep/idle cell detector* to *emulate* a mobile carrier Spectrum Provider. We built an application which uses the standard "cell search procedure" available on COTS UEs to record the availability of cell towers operating on specific cellular bands. This application executes on COTS UEs distributed across the Powder platform, and reports back to a centralized detector, which determines when cells are idled and uses that information to emulate a cooperating mobile carrier via the ZeAL Spectrum Provider API. The data collected includes the cell identifier, the frequency the cell is transmitting, and the RSRP. The detector determines the maximum RSRP value observed for all cells in the band of interest as observed by associated observation points. If this system-wide maximum RSRP value is less than a threshold, the detector decides that the band is effectively unused in the area covered by the detector, and signals the availability of spectrum to the ZMS. Whenever the system-wide maximum RSRP value exceed this threshold, the spectrum use is revoked.

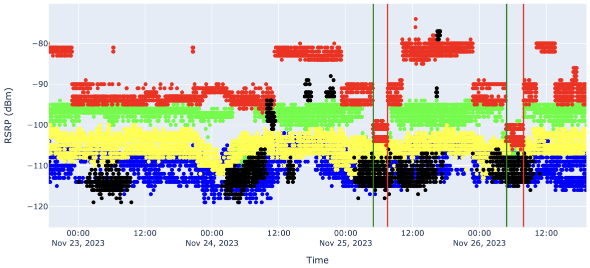

Fig. 8: Idle cell detector emulating cooperating mobile carrier

Figure 8 shows example output of the detector superimposed on the underlying data from the COTS UEs used by the detection system. Specifically, the figure shows RSRP values, associated with cells operating in the "sleeping band", as observed by the UEs used in the detector as a function of time. Our detector collected data at five different COTS UEs deployed at fixed endpoints. Cells observed from the same detector location are displayed with the same color. The superimposed vertical green and red lines respectively represent when the monitor decides to provide and revoke spectrum, thus emulating the mobile carrier notifications. (The maximum RSRP threshold used in Figure 8 was -99dBm.)

Finally, as shown at the top of Figure 7, we implemented an *emulated* radio telescope Spectrum Provider. There are two modes of operation for sensitive spectrum providers: exclusive access or shared access. The ZMS allows spectrum sharing on a temporal basis by allowing other consumers to operate when the sensitive spectrum provider is not operating. In the shared access case, the ZMS decides which consumers can operate in the same frequency range as the sensitive spectrum provider without causing harmful interference. The sensitive spectrum monitors are used by the ZMS to enforce the interference constraints and respond to any interference reports by revoking access from potential interferers. We implemented a variant of this spectrum provider where the radio telescope uses its own RF monitors to detect interference and report that to the OpenZMS to take corrective action.[5]

V. EVALUATION

Powder-RDZ combines numerous (complex) components into a coherent prototype RDZ. A thorough evaluation of each of these components is beyond the scope of this paper. Instead we focus on demonstrating the generality of the Powder-RDZ architecture and specifically its utility in realizing end-to-end RDZ workflows. We therefore focus our evaluation on an end-to-end functional illustration/evaluation of one of the RDZ workflows realized in the Powder-RDZ. We specifically use the PEL use-case described in Section II-A.

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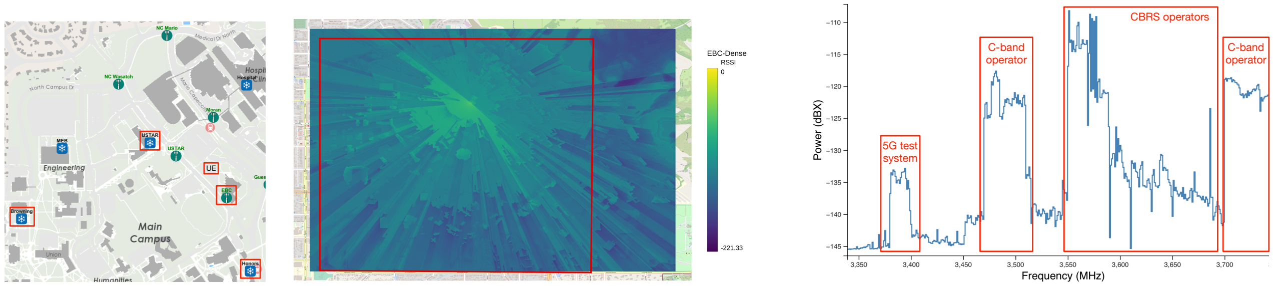
[5] We first implemented this as an end-to-end standalone RDZ use case and, at the time of writing, are porting that functionality onto OpenZMS.



(a) Partial POWDER map (b) Check TX power outside RDZ (step #5) (c) RF monitor data with 5G test system (step #6)

Fig. 9

A. Evaluation setup

Figure 7 depicts the two experimental setups used for our evaluation, as well as steps used in the end-to-end workflow. (These steps are the same as those for the corresponding use-case described in Section II-A and shown in Figure 1.)

These two setups are functionally equivalent, involving an experimental end-to-end 5G system made up of a 5G COTS UE (a Quectel RM520N) connecting to an SDR-based gNodeB (an NI B210 and Intel NUC compute node executing srsRAN software), which connects to a 5G Core instance (Open5GS software executing on a Dell R430 compute node). One version of this setup is deployed in the POWDER outdoor environment and enables over-the-air functionality, while the other is deployed in our controlled-RF environment consisting of equipment in RF-shielded enclosures interconnected through a programmatically controllable RF attenuator matrix. The outdoor over-the-air variant allows us to test POWDER-RDZ under real-world RF channel conditions but doesn't allow us to show the effects of interference from incumbents if the center frequency of operation is poorly chosen, as doing so would generate interference toward licensed transmitters. The controlled-RF variant allows us to show the effect of operating without using the spectrum intelligence provided by OPENZMS, and attempt to transmit in the presence of real-world interference signals without impacting incumbents. As shown in Figure 7, the attenuator matrix setup included two additional NI X310 SDRs with Dell R430 compute nodes (in green). We used one of these SDRs to "play back" an RF interference trace collected in the POWDER-RDZ outdoor setting, and the other to monitor the RF environment within the setup to visualize its functionality. Other than this "visualization" monitoring, all other monitoring and RDZ decision-making in our evaluation involves data from the POWDER outdoor environment. The outdoor evaluation took place weeks after the controlled-RF evaluation, leading to differences in monitor data and existing spectrum grants, and resulting in different spectrum allocations for the 5G test system.

B. End-to-end functional evaluation

In this section, we show representative "snapshots" of results obtained in the end-to-end PEL use-case depicted in Figure 7. Figure 9a shows a part of the POWDER deployment with relevant nodes marked. For the outdoor evaluation, the EBC dense site was used as the gNodeB, and a COTS UE was deployed approximately 125 m from the site, where it attached to the cell and collected link metrics.

To facilitate RF interference playback in the controlled-RF environment, we collected IQ samples using an X310 SDR at the POWDER USTAR rooftop location, with a 200 MHz sample rate and centered at 3.5 GHz. (Step #0 in Figure 7.) This trace showed similar incumbent activity to that seen in Figure 9c in that range, i.e., a C-band operator (the 40 MHz signal from 3.47-3.51 GHz) and a few 20 MHz CBRS operators (from 3.55-3.6 GHz). During the indoor controlled-RF evaluation, this trace was played back to emulate the expected real-world interference. In the outdoor evaluation, similar activity was still present.

In the end-to-end PEL workflow OPENZMS is informed about the PEL spectrum range (3.35-3.6 GHz) (step #1) and it requests monitoring data from an RF monitor (step #2). In our example flow this monitor executed on the POWDER Browning rooftop node for the controlled-RF evaluation, and the Honors rooftop node for the outdoor evaluation. At this point the 5G test setup requests spectrum from OPENZMS to operate at the EBC dense-deployment location in the POWDER outdoor environment with 20 MHz bandwidth in the PEL range (step #3). Figure 9c (excluding the 5G test system activity, which was unoccupied and therefore eventually assigned for the outdoor evaluation) shows a snapshot of the data reported by the monitor and the resulting frequency ranges as determined by the OPENZMS for the outdoor evaluation (step #4).

Before informing the 5G test system about this operating range, OPENZMS performs a geospatial query of propagation simulations via the *dst* service, to ensure that the test transmitter will not interfere outside the RDZ (step #5). Figure 9b shows the result of this query, confirming that operating at the EBC dense-deployment location will not be a problem.

OPENZMS informs the 5G test system to operate with a center frequency at 3.39 GHz for the outdoor evaluation, and 3.45 GHz for the controlled-RF evaluation (step #6). Figure 9c shows the outdoor 5G test system operating at the designated center frequency (and well separated from the incumbents). In addition, we used the controlled-RF environment to *manually* execute the 5G test system at two other center frequencies, i.e.,

Scenario	**Center freq.** (MHz)	**Avg. CQI**	**Throughput** (Mbps)
Outdoor over-the-air:			
OpenZMS selected - no overlap	3390	11.2	20.8
Indoor controlled-RF:			
OpenZMS selected - no overlap	3450	14.1	39.6
Manual - partial overlap	3470	10	10.8
Manual - complete overlap	3490	6.7	4.88

TABLE I: 5G Test system evaluation data

at 3.47GHz and 3.49GHz, representing the scenario where, without the spectral intelligence provided by the OpenZMS, a user might simply pick a center frequency within the PEL-allowed range, thereby generating and receiving varying degrees of interference. Table I shows performance metrics for the controlled-RF evaluation under these different scenarios and the outdoor evaluation with no spectral overlap with incumbent transmitters. Specifically, the table shows the average channel quality indicator (CQI) reported by the srsRAN gNodeB as an indicator of the quality of the wireless channel, as well as the average downlink throughput (measured with iPerf3) as an indicator of application level performance. As expected, the scenarios with overlapping spectrum perform significantly worse than the OpenZMS selected case. The outdoor results are commensurate with the expected path loss and other channel impairments. While we measured the impact of poor frequency selection on the *5G test system* in a controlled-RF environment, in an RDZ such selections will of course similarly impact the incumbent operators, i.e., the exact thing the OpenZMS is preventing.

VI. Related Work

To the best of our knowledge, the idea of a national radio dynamic zone (NRDZ) was first conceived by Thomas Kidd [20], as somewhat of an "opposite" to a national radio quiet zone (NRQZ). I.e., where a NRQZ is an area with special rules to protect sensitive receivers inside the zone from "normal" transmitters on the "outside", a NRDZ as conceived by Kidd would protect normal receivers *outside* the zone from special transmitters *inside* the zone. In the US, funding from the NSF's *Spectrum Innovation Initiative* has established a community of researchers that are investigating various aspects of RDZs. A recent paper by Mariya Zheleva et. al. [9] serves as a current community consensus "snapshot" of what an RDZ is, the need for RDZ(s), the features, capabilities and challenges associated with realizing an RDZ, as well as the key required functional components. In this more recent work, the RDZ concept has been generalized to "regional-scale experimental testbeds that can enable spectrum research into – and provide real-world validation of – the coexistence of disparate active and passive [spectrum using] technologies". While clearly not regional-scale, Powder-RDZ aligns with the vision described in Zheleva's paper, and we believe is the first practical (prototype) realization of an RDZ.

The (N)RDZ concept has also been explored in the context of autonomous aerial and ground spectrum sensors in the AERPAW testbed [2]. They present early results related to spectrum compliance monitoring in the AERPAW platform. The AERPAW team has also published more recent work on formulating an approach for out-of-zone signal detection [3]. These efforts are complementary to our Powder-RDZ efforts, and we envision detection systems like these to map to the OpenZMS Spectrum Monitor interface to provide spectral intelligence to the ZMS.

Another related effort is the NRDZ project being conducted by the National Radio Astronomy Observatory [4]. The focus of their project is on developing a high-fidelity advanced spectrum monitoring (ASM) device and exploring RDZ concepts in the context of radio astronomy use cases. Our Powder-RDZ/OpenZMS efforts are focused on exploring a broad range of use-cases and specifically on creating building blocks for the realization of an eventual NRDZ.

Our work builds on various related efforts within our own group. Notably, the Powder-RDZ DST concept builds upon our earlier digital spectrum twin efforts [5], [6]. Our TIREM-based RF propagation service benefits from ML-based propagation modeling enhancements [7]. We have also performed an initial exploration of automating mobility management of test transmitters in an RDZ [8].

Our work is related to other spectrum sharing approaches, notably the CBRS ecosystem [21], [22]. In that context the CBRS spectrum access system (SAS) bears resemblance to an RDZ ZMS. However, the SAS ecosystem is a single-purpose system built for a well-defined use case: to share the CBRS band in the United States. As such, the CBRS SAS ecosystem lacks the interfaces and mechanisms necessary to ensure deconflicted, parallel spectrum use; offers limited visibility into competing use within the region; lacks a model for spectrum agility and policy, e.g., spectrum providers cannot delegate a new band for the SAS to manage and use; and aims to support an emerging business model, as opposed to enabling broader spectrum sharing testing and exploration in an RDZ. For these reasons, in the OpenZMS architecture, we deliberately chose to develop a novel set of interfaces (i.e., ZeAL) and services that will support a wide variety of spectrum-sharing use cases in varied RDZ realizations.

Another related spectrum management effort is a framework [23] built on the COSMOS testbed [24] in which collaborative wireless networks exchange IEEE Spectrum Consumption Models [25] to coordinate shared spectrum use, assisted by service and monitoring planes. Our work takes a regionally-centralized approach so that RDZ participants may only consume and observe spectrum via authority granted through central mechanism, policy, and optimization decisions; and so that the ZMS can act authoritatively to remove harmful interference when violations are detected. We are investigating the application of SCMs to OpenZMS scheduling algorithms and inter-RDZ cooperation at zone boundaries.

VII. Discussion and Conclusion

In this paper we described our work on Powder-RDZ in which we presented the first end-to-end realization of a radio dynamic zone (RDZ) architecture and implementation. We illustrated the generality of our design by describing how POWDER-RDZ enables a variety of spectrum sharing use cases. We presented the design and implementation of OPENZMS, an open source zone management system (ZMS), and showed how its cloud-native modular realization eases the integration of different ZMS services and components, including commercial tools. We presented an illustrative end-to-end functional evaluation of our work on the POWDER platform, by showing the importance of ZMS-based spectrum intelligence in managing spectrum in a mobile and wireless testbed.

While "running code" in an operational testbed is a significant step forward, we realize that there is a long way to go towards the ultimate goal of a national radio dynamic zone (NRDZ). We also realize that reaching that goal will require collaboration and cooperation of the broader RDZ community. Thus, it was important for us to design the POWDER-RDZ with the objective of supporting RDZ facilities other than *our* testbed (POWDER), and specifically to make OPENZMS open source. We anticipate that the OPENZMS framework will enable others to explore RDZ concepts without the need to develop everything from the ground-up. Further, as we have shown in this paper, the flexibility of the POWDER platform serves as an ideal sandbox for RDZ related exploration.

We will continue to build on the work described here. Specifically, we will continue to develop, test and validate end-to-end RDZ use-cases and the OPENZMS components that enable them. This includes using OPENZMS as the authoritative spectrum manager in POWDER, evaluating the robustness and scalability of OPENZMS, evaluating the fidelity and accuracy of POWDER-RDZ monitoring systems, and more.

REFERENCES

[1] M. Parvini, A. H. Zarif, A. Nouruzi, N. Mokari, M. R. Javan, B. Abbasi, A. Ghasemi, and H. Yanikomeroglu, "A comprehensive survey of spectrum sharing schemes from a standardization and implementation perspective," 2022.

[2] S. J. Maeng, I. Güvenç, M. L. Sichitiu, B. Floyd, R. Dutta, T. Zajkowski, O. Ozdemir, and M. Mushi, "National radio dynamic zone concept with autonomous aerial and ground spectrum sensors," in *2022 IEEE International Conference on Communications Workshops (ICC Workshops)*, 2022, pp. 687–692.

[3] S. Joon Maeng, I. Güvenç, M. L. Sichitiu, and O. Ozdemir, "Out-of-zone signal leakage sensing in radio dynamic zones," in *ICC 2022 - IEEE International Conference on Communications*, 2022, pp. 5579–5584.

[4] C. De Pree, V. Bogan, D. Bordenave, K. Shoemaker, and A. Beasley, "The NRAO national radio dynamic zone (NRDZ) project: Current status," in *American Astronomical Society Meeting Abstracts*, vol. 55, no. 2, 2023, pp. 365–05.

[5] G. D. Durgin, M. A. Varner, N. Patwari, S. K. Kasera, and J. Van der Merwe, "Digital spectrum twinning for next-generation spectrum management and metering," in *2022 IEEE 2nd International Conference on Digital Twins and Parallel Intelligence (DTPI)*, 2022, pp. 1–6.

[6] S. Tadik, K. M. Graves, M. A. Varner, C. R. Anderson, D. Johnson, S. K. Kasera, N. Patwari, J. Van der Merwe, and G. D. Durgin, "Digital spectrum twins for enhanced spectrum sharing and other radio applications," *IEEE Journal of Radio Frequency Identification*, pp. 1–1, 2023.

[7] S. Tadik, M. A. Varner, F. Mitchell, and G. D. Durgin, "Augmented rf propagation modeling," *IEEE Journal of Radio Frequency Identification*, vol. 7, pp. 211–221, 2023.

[8] A. Gottipati and J. Van der Merwe, "FlexRDZ: Autonomous mobility management for radio dynamic zones," in *IEEE Future Networks World Forum*, 2023.

[9] M. Zheleva, C. R. Anderson, M. Aksoy, J. T. Johnson, H. Affinnih, and C. G. DePree, "Radio dynamic zones: Motivations, challenges, and opportunities to catalyze spectrum coexistence," *IEEE Communications Magazine*, vol. 61, no. 6, pp. 156–162, 2023.

[10] J. Breen, A. Buffmire, J. Duerig, K. Dutt, E. Eide, A. Ghosh, M. Hibler, D. Johnson, S. K. Kasera, E. Lewis, D. Maas, C. Martin, A. Orange, N. Patwari, D. Reading, R. Ricci, D. Schurig, L. B. Stoller, A. Todd, J. Van der Merwe, N. Viswanathan, K. Webb, and G. Wong, "POWDER: Platform for open wireless data-driven experimental research," *Computer Networks*, vol. 197, October 2021.

[11] B. C. Terry, A. Orange, N. Patwari, S. K. Kasera, and J. Van der Merwe, "Spectrum monitoring and source separation in POWDER," in *Proceedings of the 14th International Workshop on Wireless Network Testbeds, Experimental Evaluation and Characterization (WiNTECH)*, September 2020, pp. 25–32.

[12] S. J. Maeng and O. Ozdemir, "Kriging-based 3-d spectrum awareness for radio dynamic zones using aerial spectrum sensors," 2023, https://doi.org/10.48550/arXiv.2307.06310.

[13] G. D. Durgin, M. A. Varner, M. A. Weitnauer, J. Cressler, M. M. Tentzeris, A. Zajic, S. Zeinolabedinzadeh, R. Zekavat, K. Pahlavan, U. Guler, and K. V. d. Merwe, "Digital spectrum twinning and the role of rfid and backscatter communications in spectral sensing," in *2021 IEEE International Conference on RFID Technology and Applications (RFID-TA)*, 2021, pp. 89–92.

[14] U.S. Department of Commerce, "Quantitative Assessments of Spectrum Usage," https://www.ntia.gov/report/2016/quantitative-assessments-spectrum-usage, November 2016.

[15] F. H. Sanders, R. L. Sole, J. E. Carroll, G. S. Secrest, and T. L. Allmon, "Analysis and Resolution of RF Interference to Radars Operating in the Band 2700–2900 MHz from Broadband Communication Transmitters," https://www.ntia.gov/report/2012/analysis-and-resolution-rf-interference-radars-operating-band-2700-2900-mhz-broadband, October 2012.

[16] Z. Khan, J. J. Lehtomaki, R. Vuohtoniemi, E. Hossain, and L. A. Dasilva, "On opportunistic spectrum access in radar bands: Lessons learned from measurement of weather radar signals," *IEEE Wireless Communications*, vol. 23, no. 3, pp. 40–48, 2016.

[17] D. R. DeBoer, S. L. Cruz-Pol, M. M. Davis, T. Gaier, P. Feldman, J. Judge, K. I. Kellermann, D. G. Long, L. Magnani, D. S. McKague, T. J. Pearson, A. E. E. Rogers, S. C. Reising, G. Taylor, A. R. Thompson, and L. van Zee, "Radio frequencies: Policy and management," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 51, no. 10, pp. 4918–4927, 2013.

[18] D. Eppink and W. Kuebler, *TIREM/SEM Handbook*. IIT Research Institute, Tech. Rep., Sept 1986.

[19] "NTIA/ITS SCOS Sensor," https://github.com/NTIA/scos-sensor.

[20] T. Kidd, "National radio quiet and dynamic zones," *CHIPS, the Department of the Navy's Information Technology Magazone*, April–June 2018.

[21] M. M. Sohul, M. Yao, T. Yang, and J. H. Reed, "Spectrum access system for the citizen broadband radio service," *IEEE Communications Magazine*, vol. 53, no. 7, pp. 18–25, July 2015.

[22] C. W. Kim, J. Ryoo, and M. M. Buddhikot, "Design and implementation of an end-to-end architecture for 3.5 ghz shared spectrum," in *2015 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, 2015, pp. 23–34.

[23] D. Stojadinovic, P. Netalkar, C. E. C. Bastidas, I. Kadota, G. Zussman, I. Seskar, and D. Raychaudhuri, "A spectrum consumption model-based framework for dsa experimentation on the cosmos testbed," in *Proceedings of the 15th ACM Workshop on Wireless Network Testbeds, Experimental Evaluation & CHaracterization*, 2021, p. 77–84.

[24] D. Raychaudhuri, I. Seskar, G. Zussman, T. Korakis, D. Kilper, T. Chen, J. Kolodziejski, M. Sherman, Z. Kostic, X. Gu, H. Krishnaswamy, S. Maheshwari, P. Skrimponis, and C. Gutterman, "Challenge: COSMOS: A city-scale programmable testbed for experimentation with advanced wireless," in *Proceedings of the 26th Annual International Conference on Mobile Computing and Networking (MobiCom)*, September 2020.

[25] C. E. C. Bastidas, J. A. Stine, A. Rennier, M. Sherman, A. Lackpour, M. M. Kokar, and R. Schrage, "Ieee 1900.5.2: Standard method for modeling spectrum consumption: Introduction and use cases," *IEEE Communications Standards Magazine*, vol. 2, no. 4, pp. 49–55, 2018.